US010011022B1

(12) United States Patent
Lin et al.

(10) Patent No.: US 10,011,022 B1
(45) Date of Patent: Jul. 3, 2018

(54) **ROBOTIC SYSTEM WITH RECONFIGURABLE END-EFFECTOR ASSEMBLY**

(71) Applicant: **GM GLOBAL TECHNOLOGY OPERATIONS LLC**, Detroit, MI (US)

(72) Inventors: **Yhu-tin Lin**, Rochester Hills, MI (US); **Dooil Hwang**, Rochester Hills, MI (US); **Maurice Perlman**, Oak Park, MI (US)

(73) Assignee: **GM GLOBAL TECHNOLOGY OPERATIONS LLC**, Detroit, MI (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **15/440,471**

(22) Filed: **Feb. 23, 2017**

(51) **Int. Cl.**
B25J 15/00 (2006.01)
B25J 9/10 (2006.01)
B25J 15/06 (2006.01)

(52) **U.S. Cl.**
CPC ***B25J 15/0061*** (2013.01); ***B25J 9/1005*** (2013.01); ***B25J 15/0616*** (2013.01)

(58) **Field of Classification Search**
CPC B25J 15/0061; B25J 15/0052; B25J 15/0616; B25J 9/04; B25J 9/1005; B65G 47/91; Y10S 901/40; Y10S 901/14; Y10S 901/23; Y10S 901/30; Y10S 901/19
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

7,575,408	B2 *	8/2009	Tominaga	B25J 15/0052 414/222.04
8,172,210	B2 *	5/2012	Jeon	B25J 15/0061 269/21
8,857,877	B2	10/2014	Lin et al.	
2009/0035107	A1 *	2/2009	Duran	B25J 5/02 414/426
2009/0194922	A1 *	8/2009	Lin	B25J 15/0052 269/55
2010/0140969	A1 *	6/2010	Lin	B25J 15/0052 294/86.4
2015/0336221	A1	11/2015	McKay	
2015/0336271	A1	11/2015	Spicer et al.	
2016/0346865	A1	12/2016	Sigler et al.	

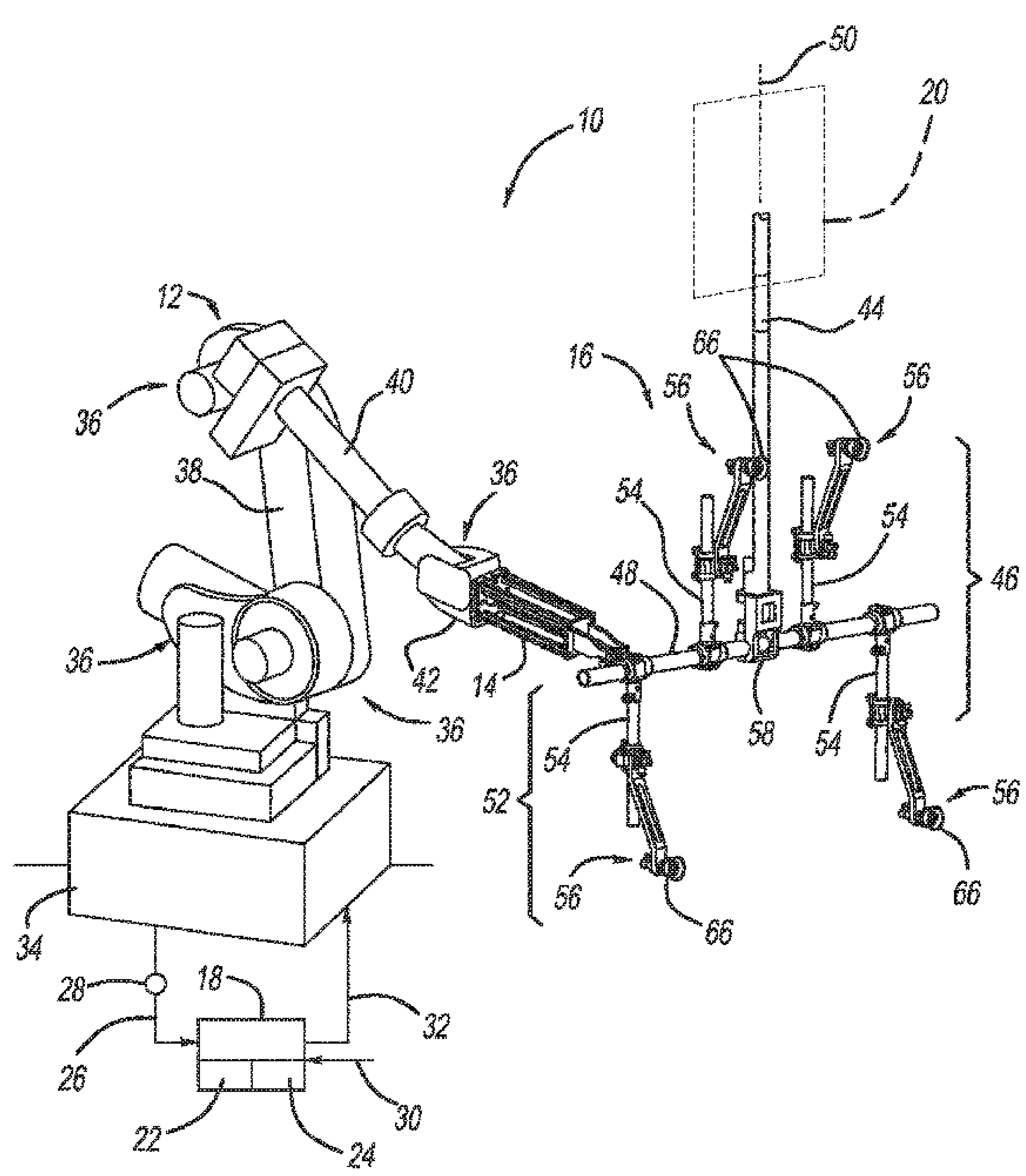
* cited by examiner

Primary Examiner — Stephen A Vu

(57) **ABSTRACT**

An end-effector assembly includes a master boom, a frame rail coupled to the master boom, at least one branch rail movably coupled to the frame rail by a branch lock, and a swing arm movably coupled to the at least one branch rail by a swing lock. The swing lock includes a clamp configured to movably secure the swing arm to the branch rail. A pivot shaft extends through the clamp and the swing arm and is configured to rotationally secure the swing arm to the clamp. A swing plate is secured to the pivot shaft and is configured for engagement with a configuration tool. Further, a locking fastener extends through the swing plate and into the pivot shaft. The locking fastener is configured to lock and unlock the swing lock in position along the branch rail.

17 Claims, 8 Drawing Sheets



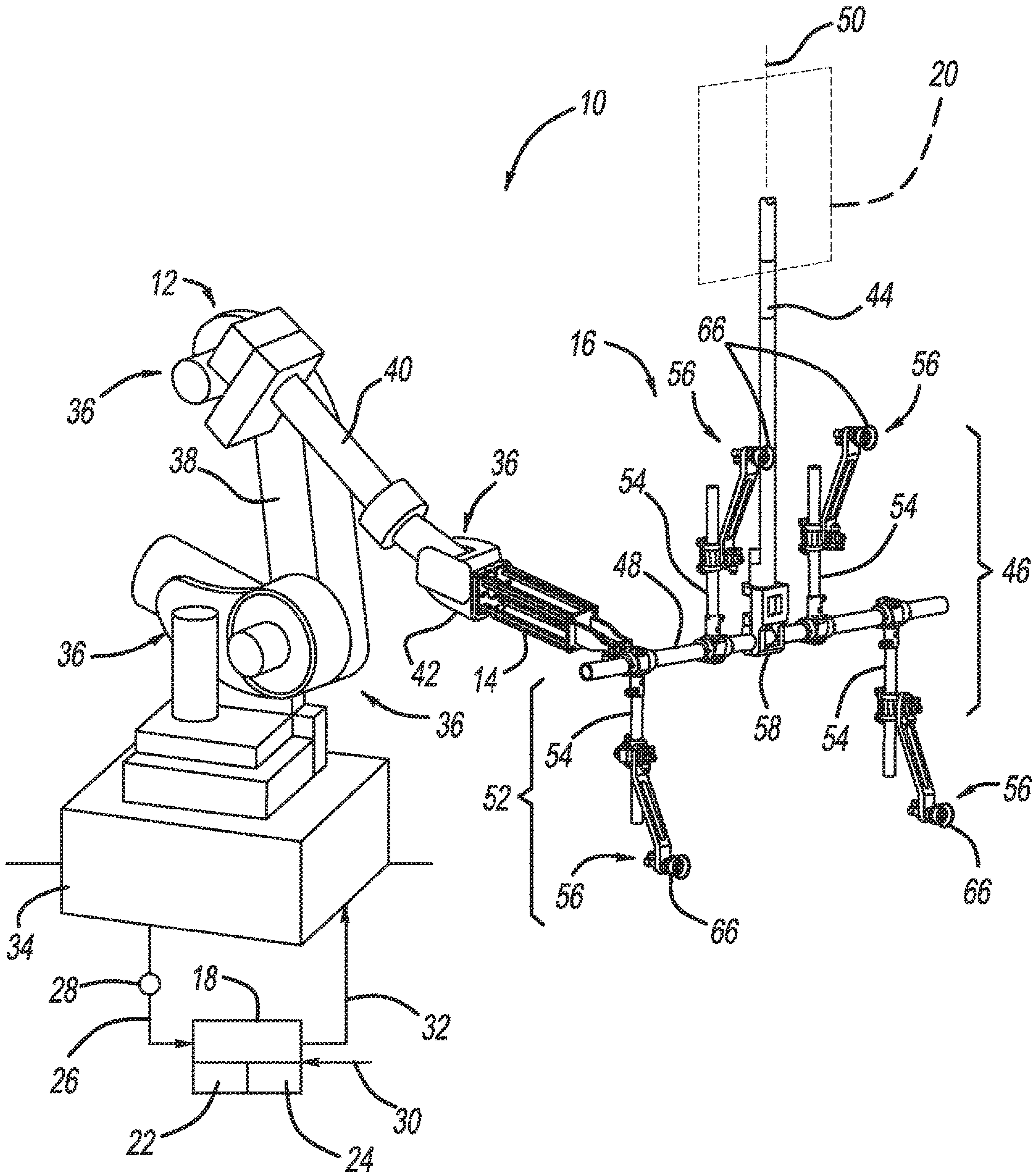

10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
52
54
56
58
66

FIG - 1

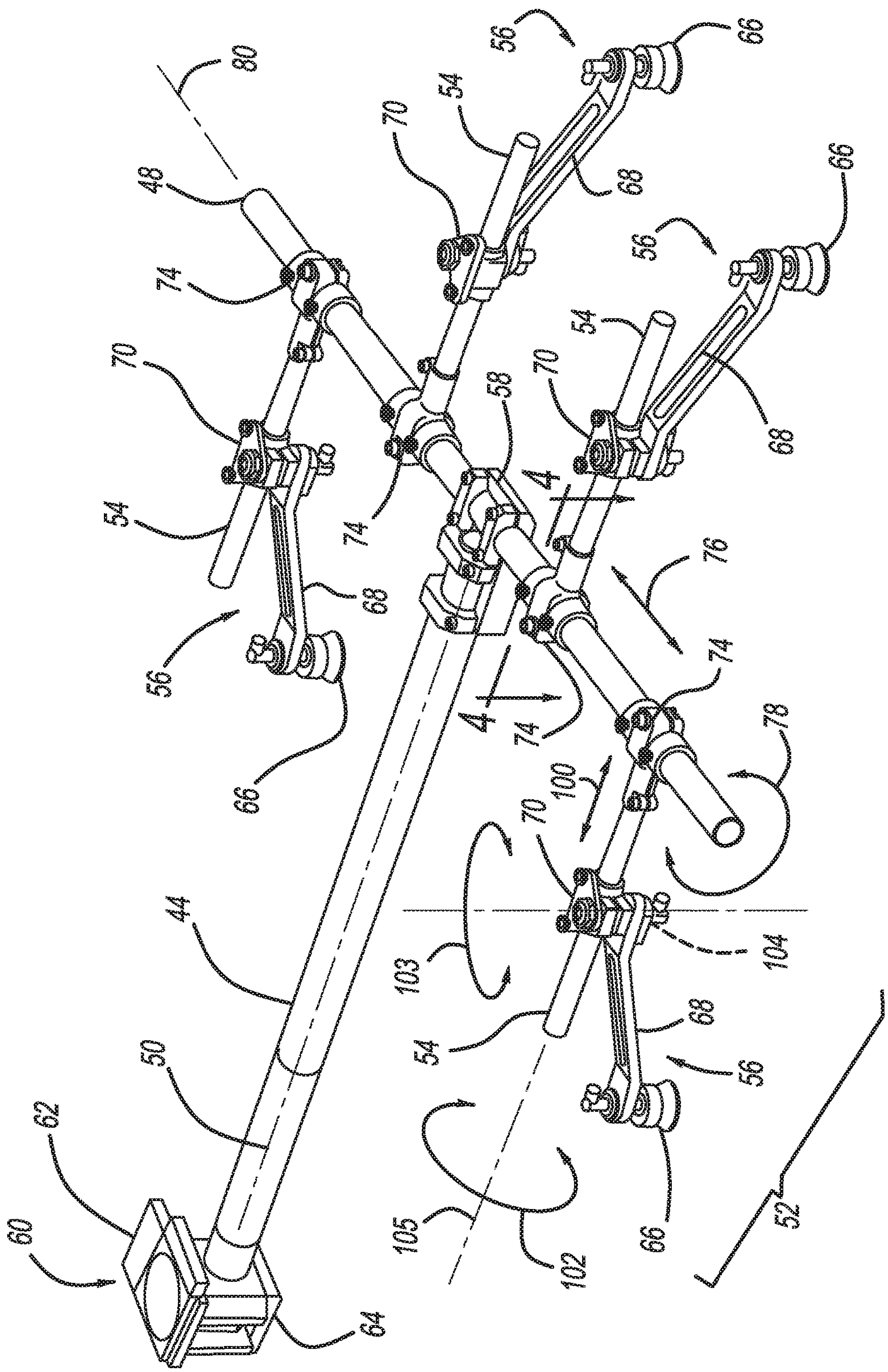

80
56
66
48
70
54
68
74
58
4
76
78
100
103
104
105
102
44
50
62
60
64
52

FIG - 2

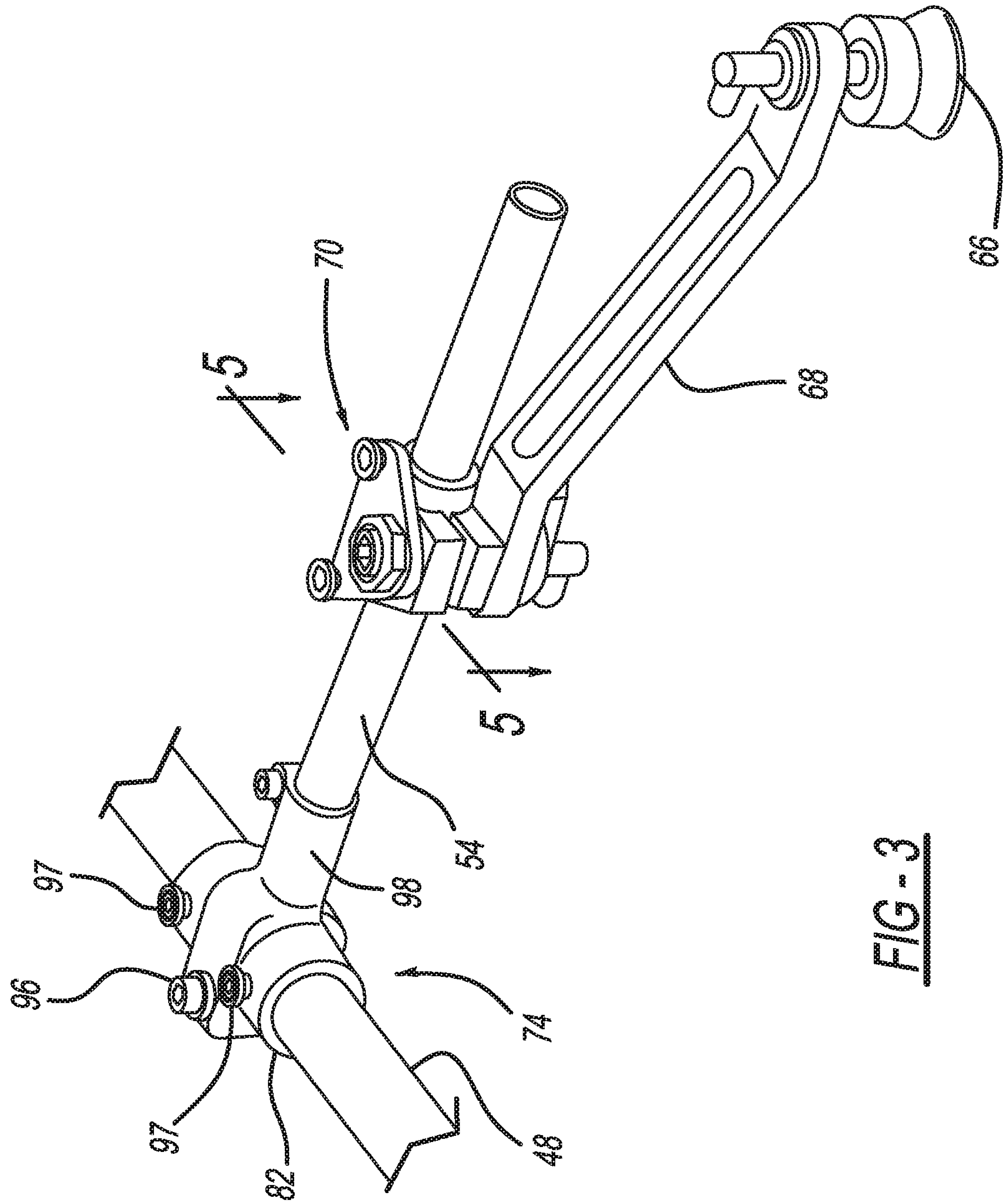


FIG - 3

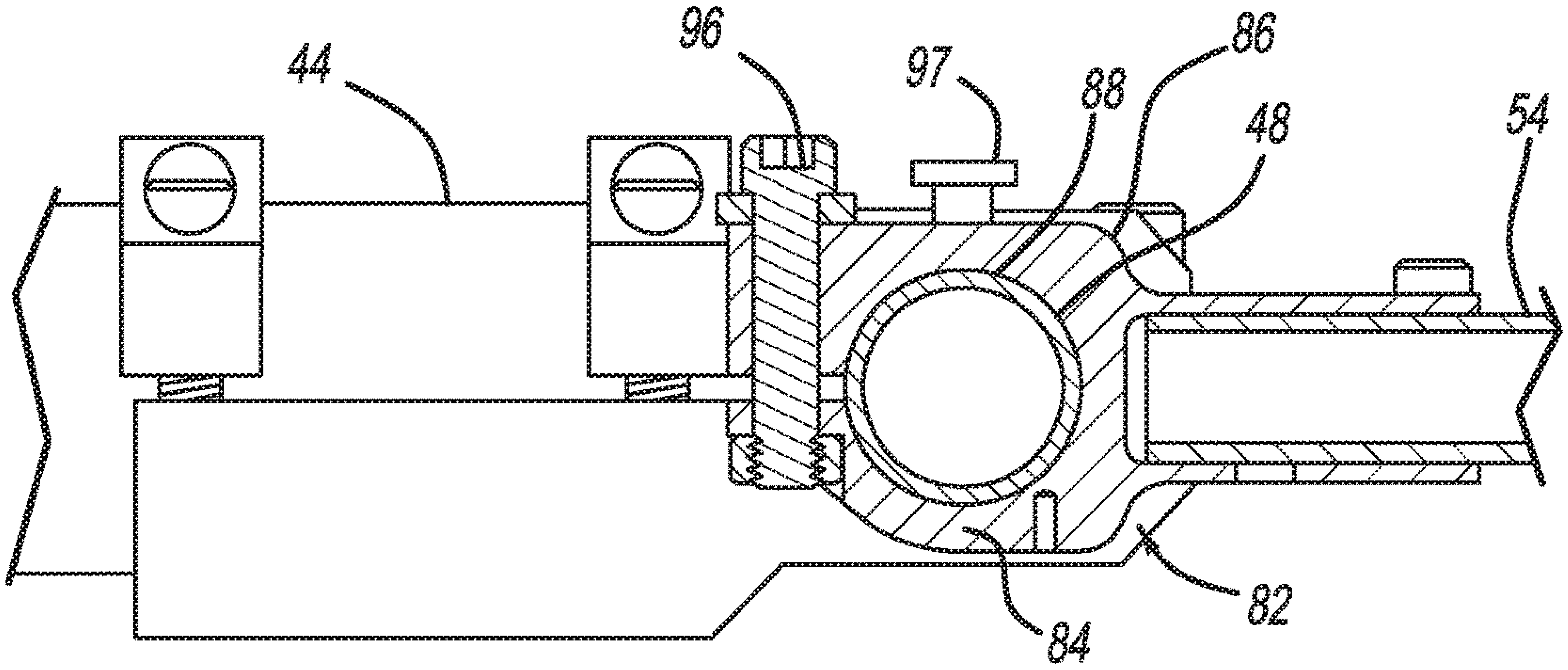

44
96
97
88
86
48
54
82
84

FIG - 4

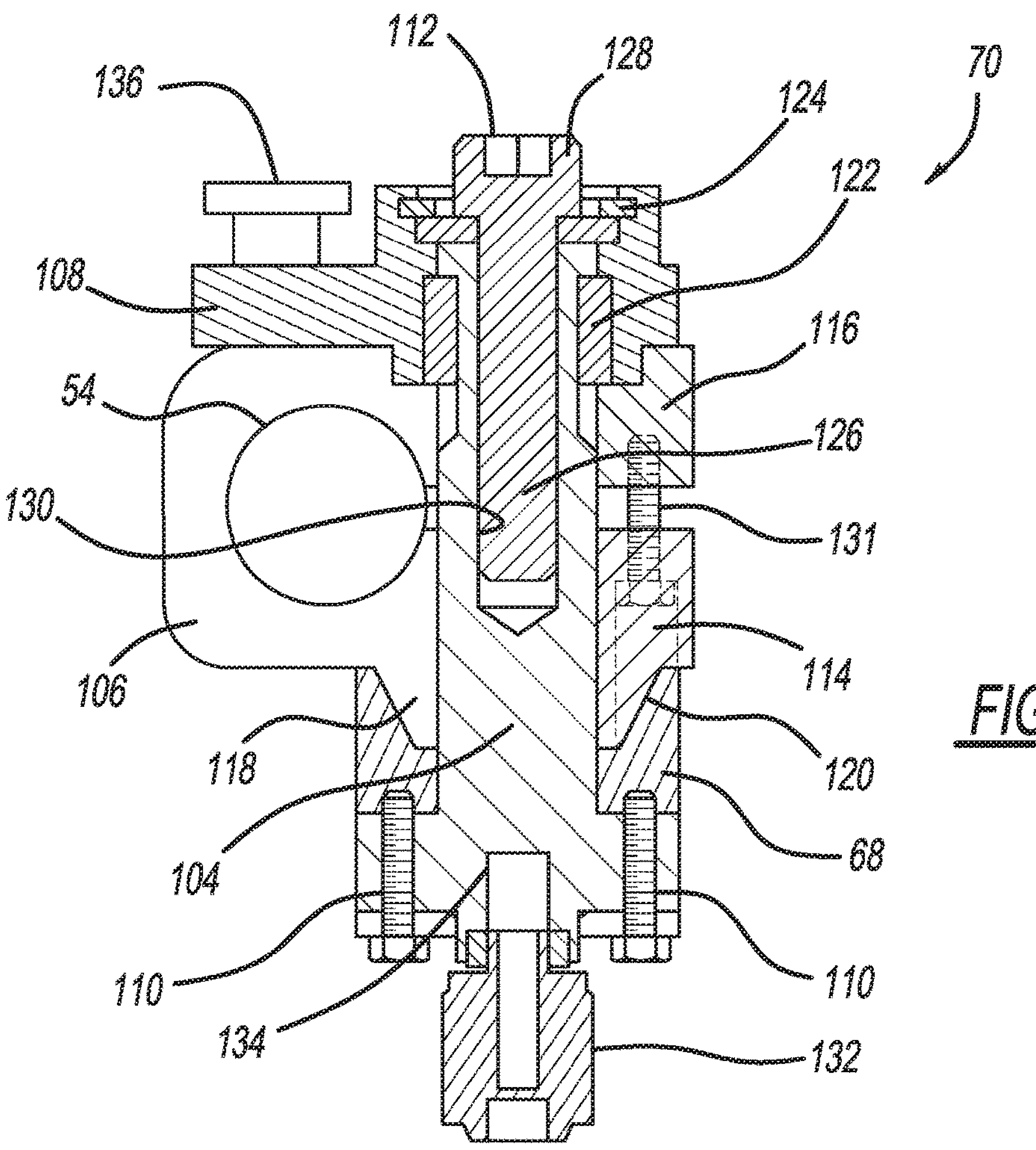

112
128
70
136
124
122
108
116
54
126
130
131
114
106
120
118
68
104
110
110
134
132

FIG - 5

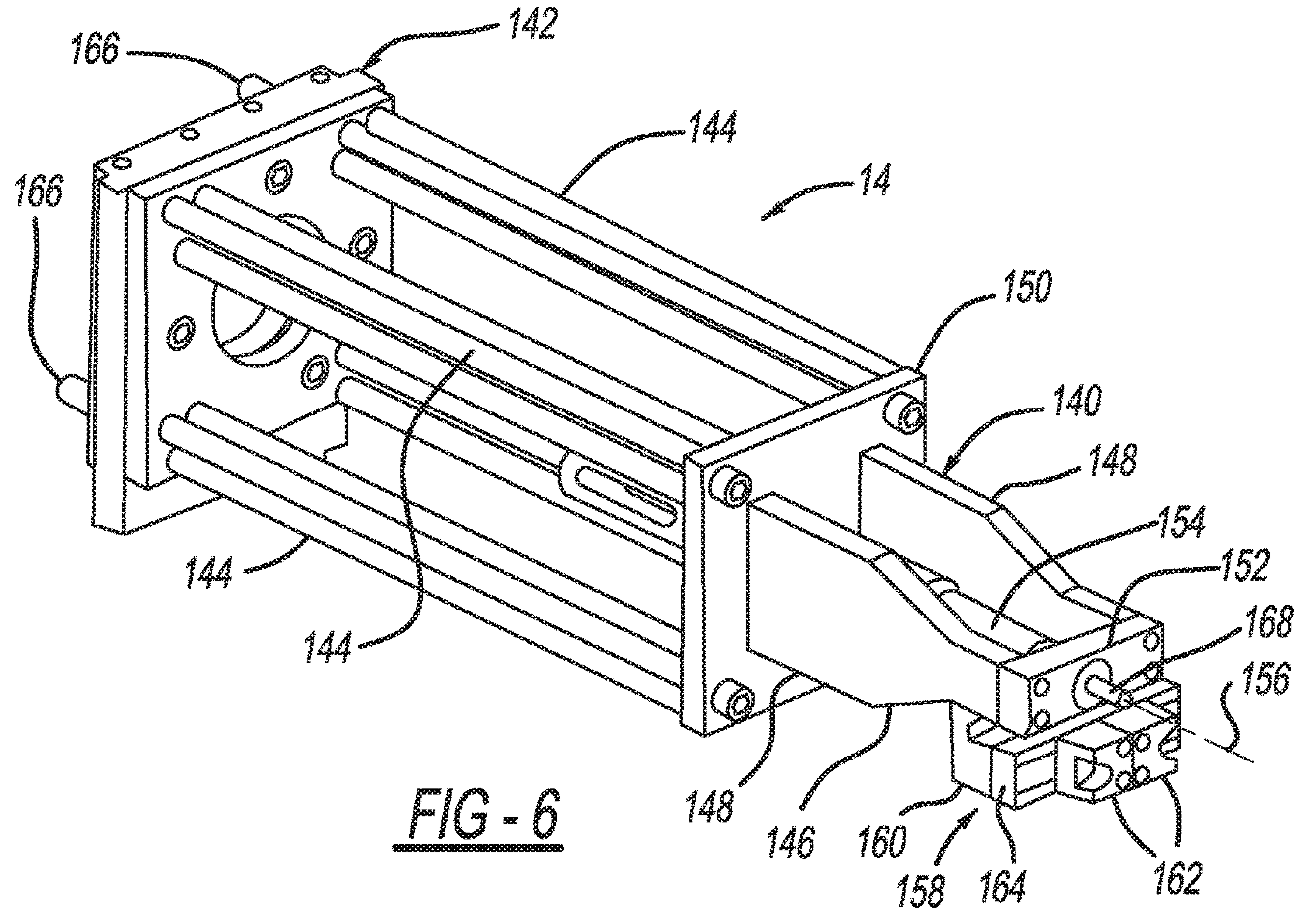

166
142
166
144
14
150
140
148
154
152
168
156
144
144
148
146
160
158
164
162

FIG - 6

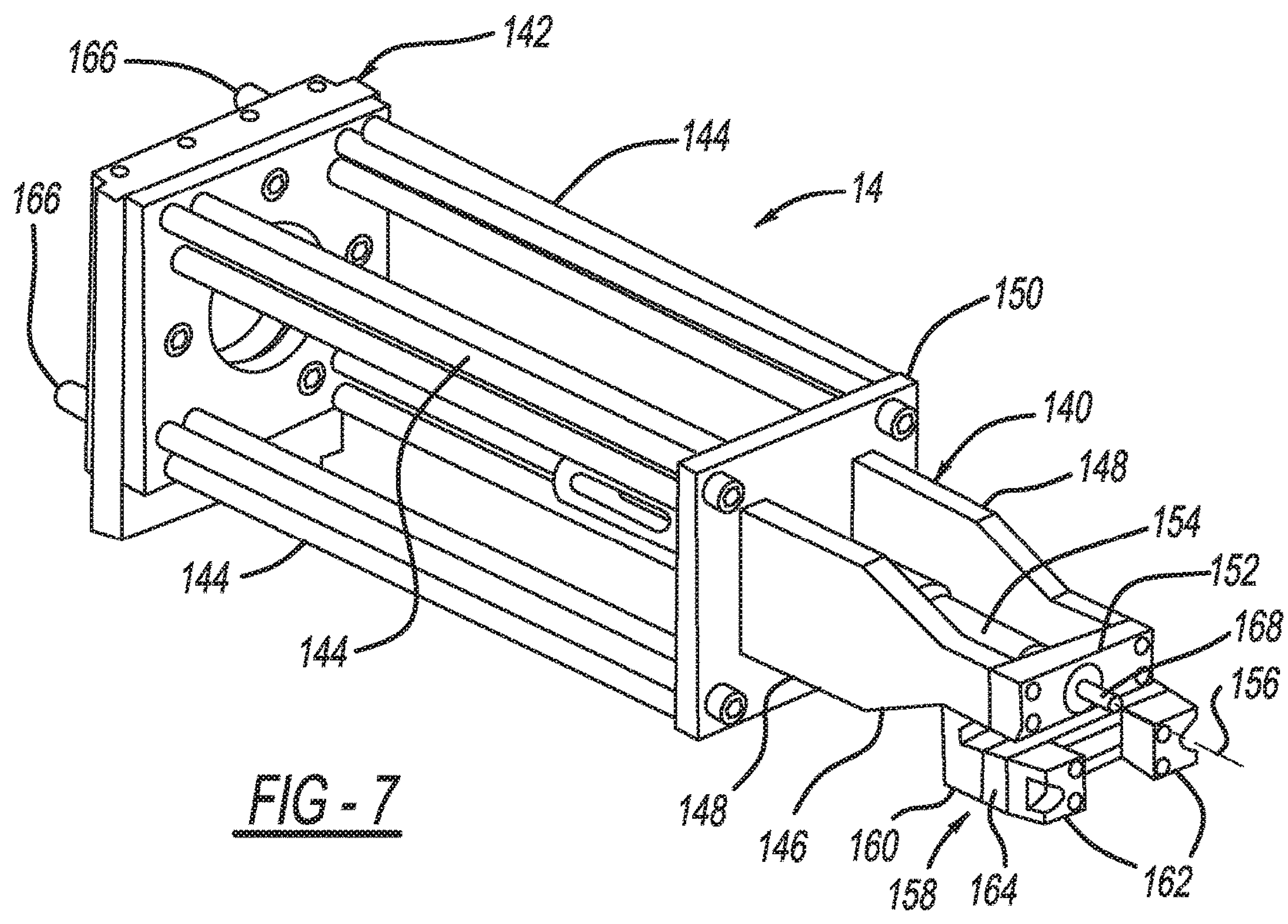

166
142
166
144
14
150
140
148
154
152
168
156
144
144
148
146
160
158
164
162

FIG - 7

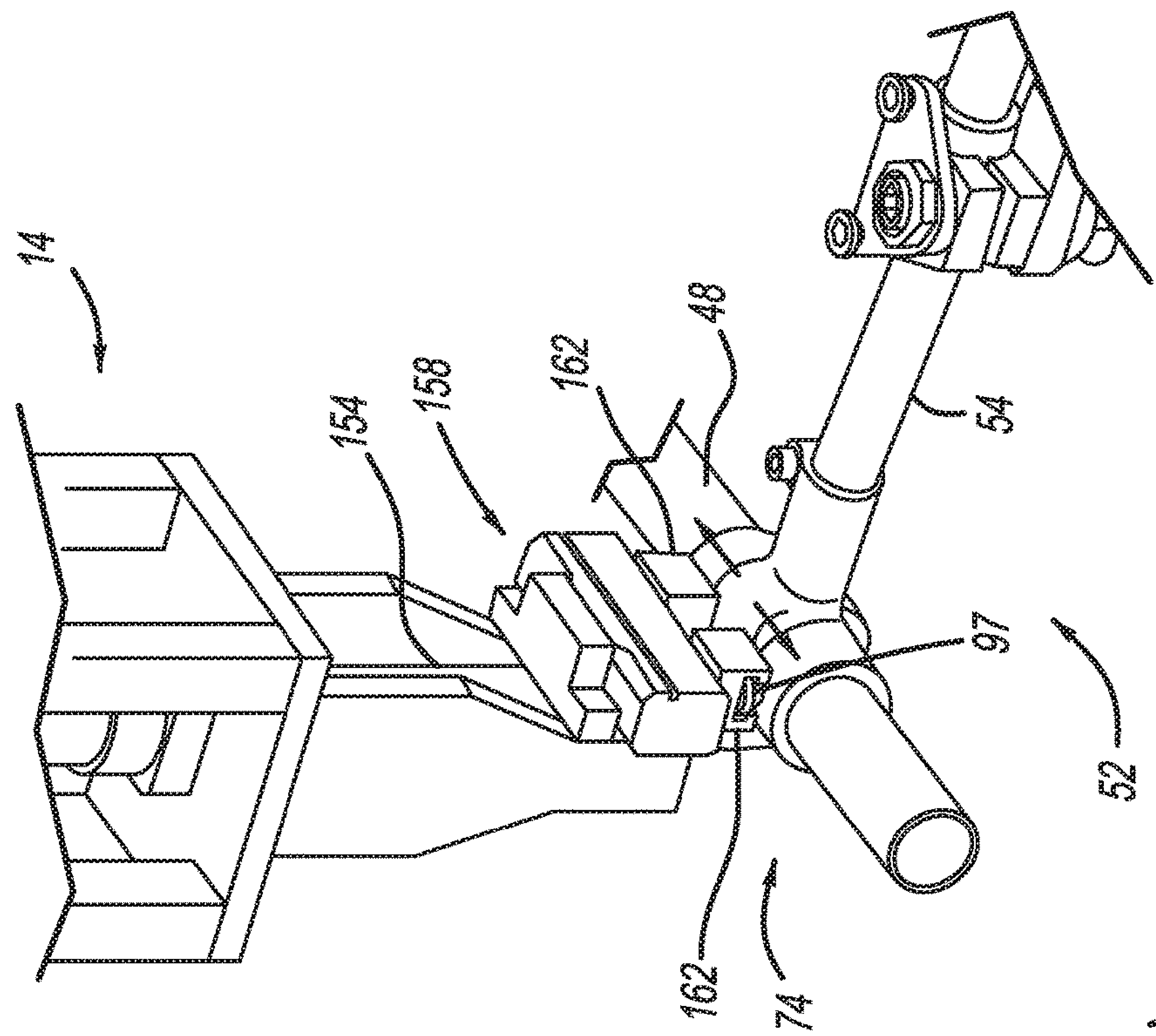

14
154
158
162
48
54
97
52
162
74

FIG - 9

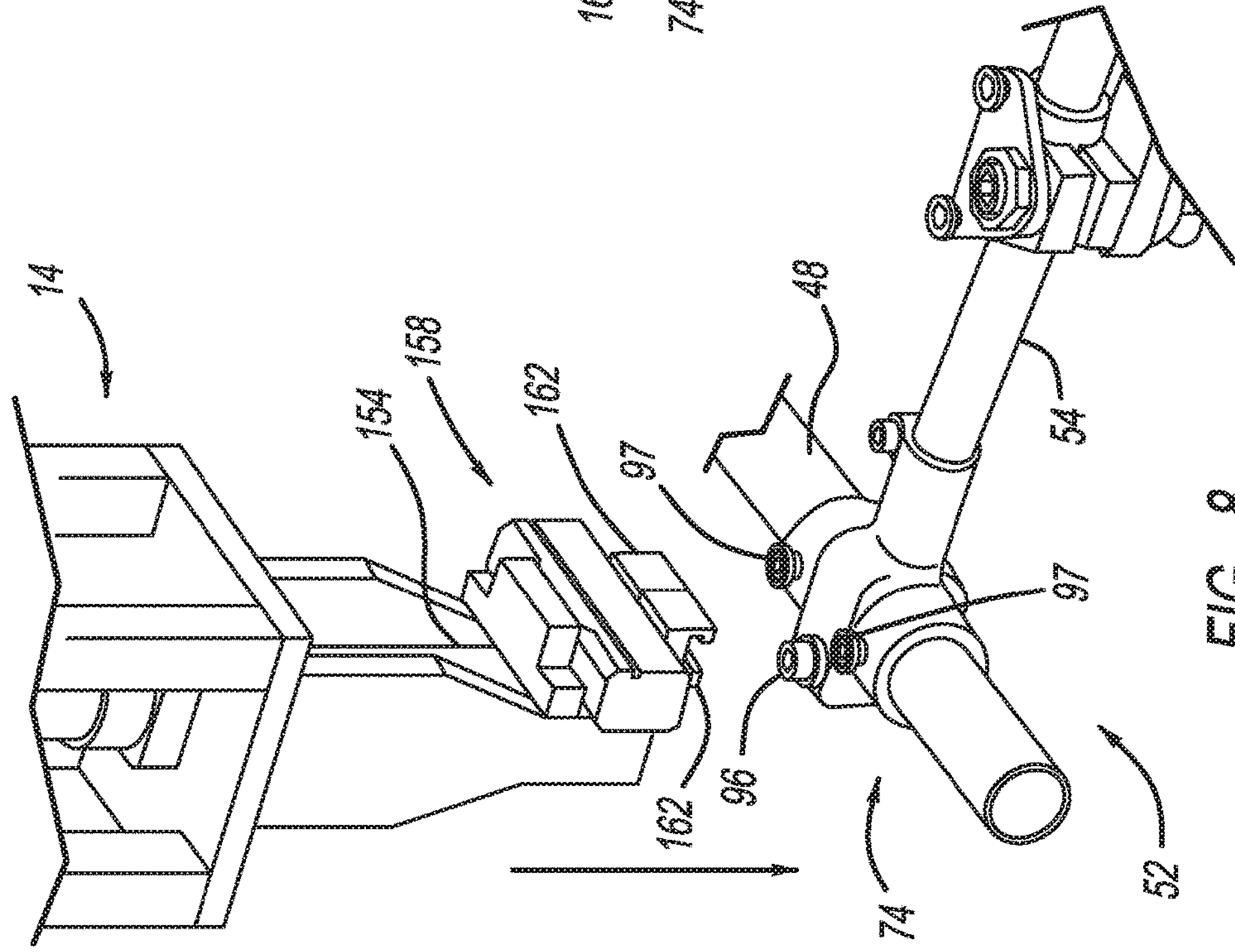

14
154
158
162
48
97
97
54
96
162
74
52

FIG - 8

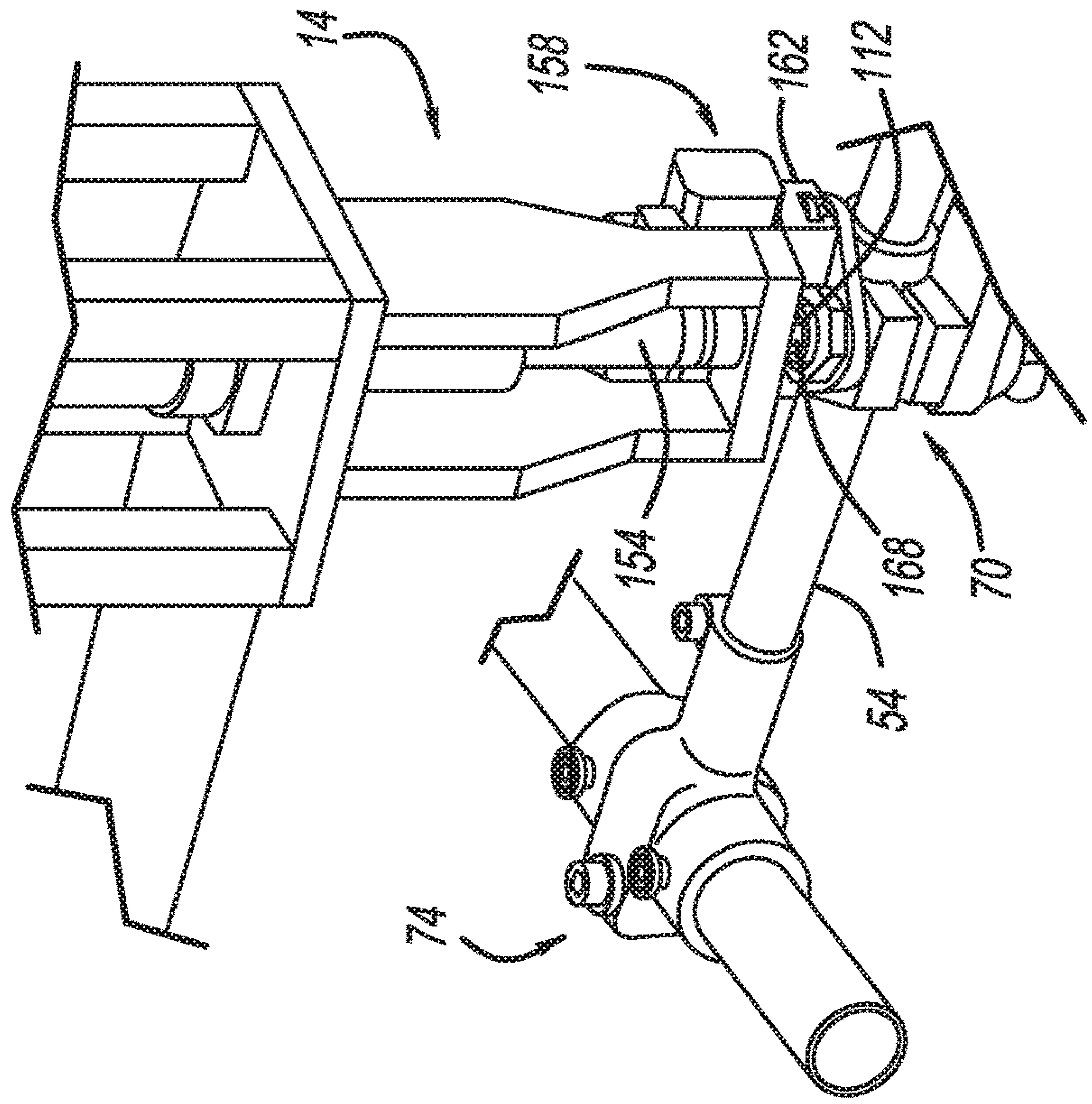


FIG - 11

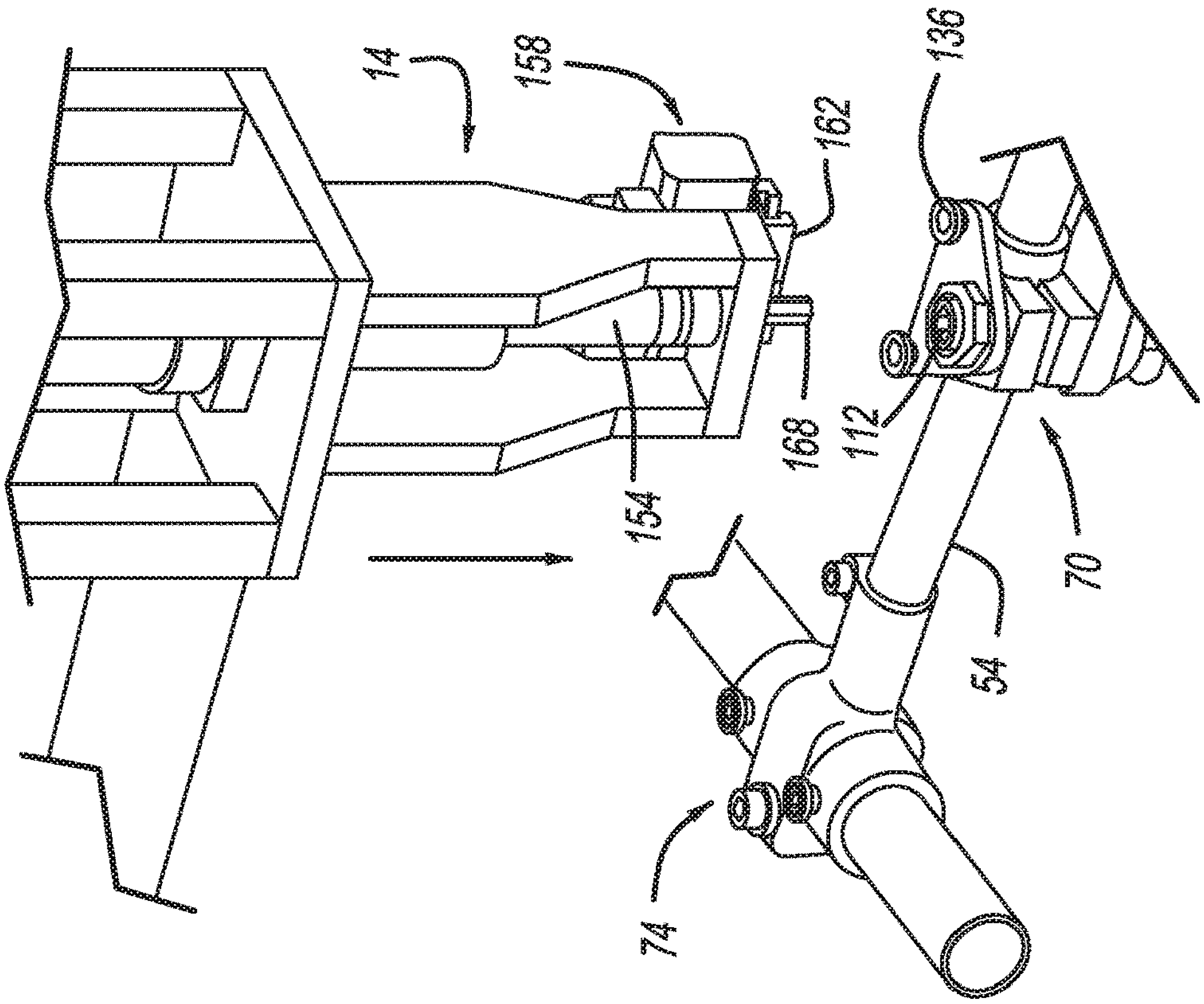


FIG - 10

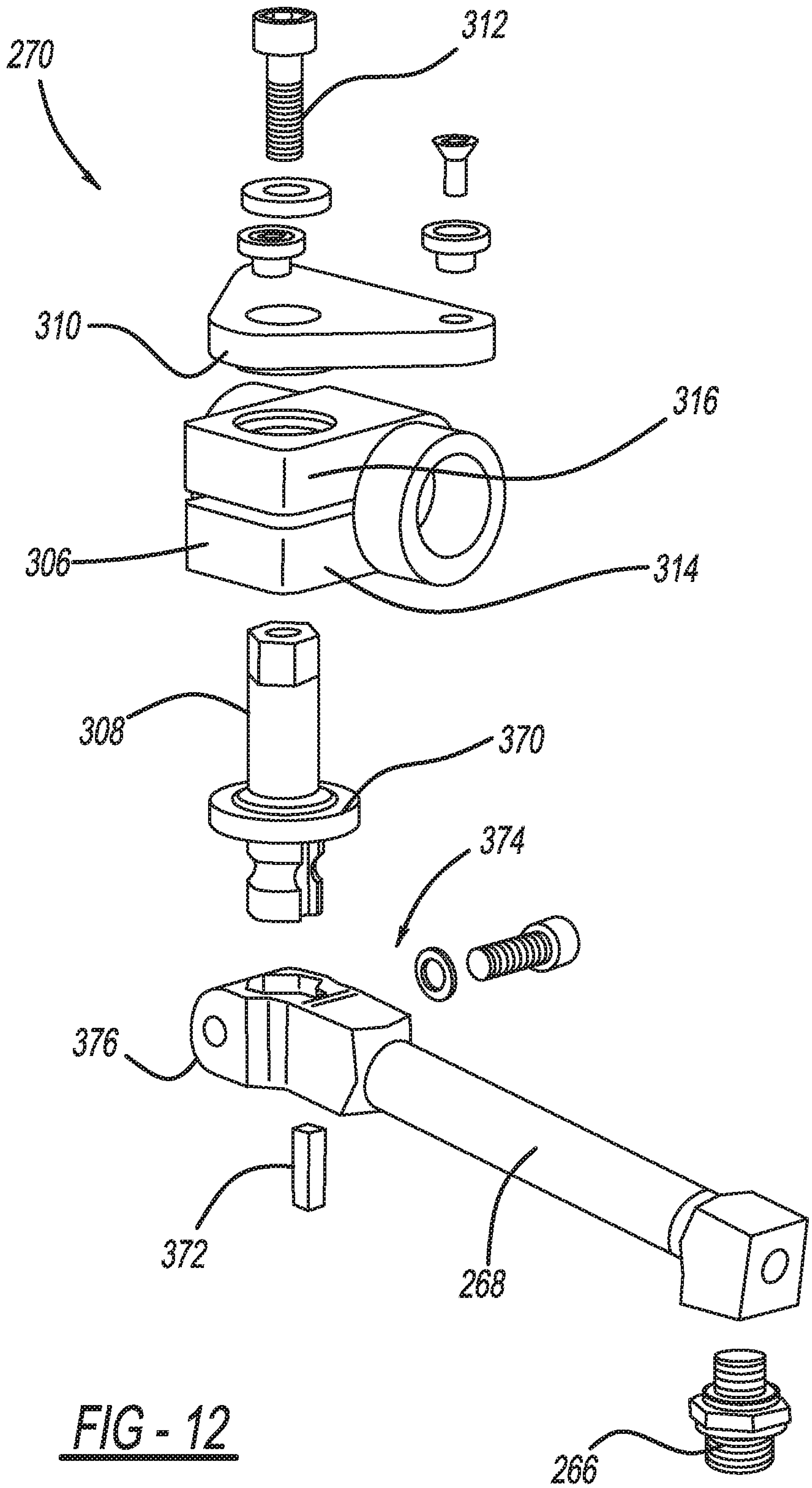


FIG - 12

ROBOTIC SYSTEM WITH RECONFIGURABLE END-EFFECTOR ASSEMBLY

FIELD

The present disclosure relates to a robotic system with a reconfigurable end-effector assembly.

INTRODUCTION

The statements in this section merely provide background information related to the present disclosure and may not constitute prior art.

Multi-axis industrial robots include articulated arms connected via joints. Each arm segment is driven via one or more joint motors. Typical industrial robots are controlled with respect to six different control axes. Collectively, the control axes enable rotation of the robot with respect to a fixed or mobile base, extension/retraction of a first arm, and raising/lowering of a second arm, as well as joint rotation and rotation/translation of a wrist disposed at a distal end of the second arm. Additional arms may be used in a serial arrangement depending on the design and an end-effector connected to the wrist may be manipulated to perform a desired work task.

The term "end-effector" refers to the particular end linkages or segments that, depending on the design of the robot, can securely grip, transport, orient, and release a workpiece. Certain end-effector assemblies are formed via a latticed array of elongated beams and/or rails to which are attached a set of tool branches suspended with end tools (e.g., suction cups or grippers of the type used for moving metal panels or panes of glass in a manufacturing facility). The individual tool branches and tool modules traditionally are manually adjusted by an operator to a predetermined configuration prior to performing a specified work task.

SUMMARY

An end-effector assembly includes a master boom, a frame rail coupled to the master boom, at least one branch rail movably coupled to the frame rail by a branch lock, and a swing arm movably coupled to the at least one branch rail by a swing lock. The swing lock includes a clamp configured to movably secure the swing arm to the branch rail. A pivot shaft extends through the clamp and the swing arm and is configured to rotationally secure the swing arm to the clamp. A swing plate is secured to the pivot shaft and is configured for engagement with a configuration tool. Further, a locking fastener extends through the swing plate and into the pivot shaft. The locking fastener is configured to lock and unlock the swing lock in position along the branch rail.

In some embodiments of the end-effector assembly, the branch lock is movable relative to the frame rail between an unlocked and a locked state so as to fix the branch rail in position relative to the frame rail. Furthermore, the swing lock is rotationally and linearly movable along the branch rail between an unlocked and a locked state so as to fix the swing arm in position relative to the branch rail. Additionally, the end-effector assembly further comprises an end tool arranged at a distal end of the swing arm, the end tool defining a first side of the end-effector assembly for engagement with a workpiece. The branch lock and the swing lock are configured to be engaged by the configuration tool on a second side of the end-effector assembly opposite to the first side. Furthermore, the clamp further defines a protrusion on an end face and the swing arm defines a correspondingly-shaped recess, and wherein the protrusion and the recess are matingly joined when the locking fastener is locked. Additionally, a retaining ring may be secured within the swing plate and configured to retain the locking fastener therein. The retaining ring traps the locking fastener to assist in releasing the protrusion from the recess. The swing lock may also include at least one over-stretch limiting device having at least one over-stretch fastener secured within the clamp for restraining the clamp during unlock of the swing lock.

A swing lock assembly for an end-effector includes a clamp configured to movably secure a swing arm to a branch rail. The clamp includes an arm portion and a base portion having a protrusion on an end face thereof. The swing arm has a recess correspondingly shaped with the protrusion. A pivot shaft extends through the arm and base portions of the clamp and is configured to rotationally secure the swing arm to the clamp. A swing plate is arranged on the arm portion of the clamp and is keyed to the pivot shaft. The swing plate includes at least one tab configured for engagement with a configuration tool. A locking fastener extends through the swing plate and into the pivot shaft. The locking fastener is configured to lock and unlock the swing lock assembly in position along the branch rail, and the protrusion and the recess are matingly joined when the locking fastener is locked.

In some embodiments, the swing lock assembly also includes a retaining ring secured within the swing plate and configured to retain the locking fastener therein. The retaining ring traps the locking fastener to assist in releasing the protrusion from the recess. Furthermore, the swing lock is rotationally and linearly movable along the branch rail between an unlocked and a locked state so as to fix the swing arm in position relative to the branch rail. Additionally, the swing lock assembly may also include an end tool arranged at a distal end of the swing arm. The end tool defines a first side of the end-effector. The swing lock assembly is configured to be engaged by the configuration tool on a second side of the end-effector opposing the first side. The swing lock assembly may also include at least one over-stretch limiting device having at least one over-stretch fastener secured between the arm portion and the base portion of the clamp for restraining the clamp during unlock of the locking fastener.

The configuration tool usable with the swing lock assembly may include a tool body, a gripper coupled to the tool body, and a driver bit extending from the tool body. The gripper includes a plurality of gripper fingers movable toward and away from each other. The configuration tool is coupled to the swing lock assembly when the gripper fingers engage the at least one tab. Furthermore, the driver bit is aligned with the locking fastener when the gripper fingers engage the at least one tab such that rotating the driver bit causes the swing lock assembly to move between the locked and unlocked states.

A swing lock assembly for an end-effector includes a clamp configured to secure a swing arm to a branch rail. The clamp has a first surface and an opposing second surface. A pivot shaft extends through the clamp and the swing arm in order to rotationally secure the swing arm to the clamp. The pivot shaft has a flange arranged at the second surface of the clamp. A swing plate is arranged on the first surface of the clamp and is keyed to the pivot shaft. The swing plate includes at least one tab configured for engagement with a configuration tool. A locking fastener extends through the swing plate and into the pivot shaft. The locking fastener is configured to move the swing plate and the flange toward each other in order to lock the swing lock assembly in position along the branch rail and away from each other in order to unlock the swing lock assembly from position along the branch rail.

In some embodiments, the swing lock assembly is rotationally and linearly movable along the branch rail between an unlocked and a locked state so as to fix the swing arm in position relative to the branch rail. Additionally, the swing lock assembly may also include an end tool arranged at a distal end of the swing arm. The end tool defines a first side of the end-effector. The swing lock assembly is configured to be engaged by the configuration tool on a second side of the end-effector opposing the first side. Furthermore, the pivot shaft may be keyed for rotational movement with the swing arm.

The configuration tool usable with the swing lock assembly may include a tool body, a gripper coupled to the tool body, and a driver bit extending from the tool body. The gripper includes a plurality of gripper fingers movable toward and away from each other. The configuration tool is coupled to the swing lock assembly when the gripper fingers engage the at least one tab. Furthermore, the driver bit is aligned with the locking fastener when the gripper fingers engage the at least one tab such that rotating the driver bit causes the swing lock assembly to move between the locked and unlocked states.

In still other embodiments, a robot has an end-effector including the swing lock assembly as described above.

Further areas of applicability will become apparent from the description provided herein. It should be understood that the description and specific examples are intended for purposes of illustration only and are not intended to limit the scope of the present disclosure.

DRAWINGS

The drawings described herein are for illustration purposes only and are not intended to limit the scope of the present disclosure in any way.

FIG. **1** is a perspective view of a robotic system including an end-effector assembly according to the present disclosure;

FIG. **2** is a perspective view of the end-effector assembly of FIG. **1**;

FIG. **3** is a perspective view of a frame rail and a tool branch of the end-effector assembly of FIG. **2**;

FIG. **4** is a cross-sectional view of the end-effector assembly, taken along section line **4-4** of FIG. **2**;

FIG. **5** is a cross-sectional view of the end-effector assembly, taken along section line **5-5** of FIG. **3**;

FIG. **6** is a perspective view of a configuration tool usable as part of the robotic system of FIG. **1**, with a gripper finger depicted in a disengaged state;

FIG. **7** is a perspective view of the configuration tool usable as part of the robotic system of FIG. **1**, with a gripper finger depicted in an engaged state;

FIG. **8** is a perspective view of the configuration tool moving toward a branch lock of the end-effector assembly;

FIG. **9** is a perspective view of the configuration tool coupled to the branch lock of the end-effector assembly;

FIG. **10** is a perspective view of the configuration tool moving toward a swing lock of the end-effector assembly;

FIG. **11** is a perspective view of the configuration tool coupled to the swing lock of the end-effector assembly; and

FIG. **12** is an exploded view of an alternative swing lock for the end-effector assembly.

DETAILED DESCRIPTION

The following description is merely exemplary in nature and is not intended to limit the present disclosure, application, or uses. It should be understood that throughout the drawings, corresponding reference numerals indicate like or corresponding parts and features. Further, directions such as "top," "side," "back", "lower," and "upper" are used for purposes of explanation and are not intended to require specific orientations unless otherwise stated. These directions are merely provided as a frame of reference with respect to the examples provided, but could be altered in alternate applications.

Referring to the drawings, wherein like reference numbers refer to like components throughout the several figures, a robotic system **10** is shown schematically in FIG. **1**. The robotic system **10** includes a multi-axis industrial robot **12**, a configuration tool **14**, and a reconfigurable end-effector assembly **16** described in detail below. Overall operational control of the robotic system **10** may be achieved via a controller **18**. The robotic system **10** also includes a configuration stand **20**, as will be discussed in greater detail below.

The controller **18** may be configured as a host machine (e.g., a digital computer), which is specially programmed to execute steps or instructions. To that end, the controller **18** includes sufficient hardware to perform the required method steps, i.e., with sufficient memory **22**, a processor **24**, and other associated hardware such as a high-speed clock, analog-to-digital and/or digital-to-analog circuitry, a timer, input/output circuitry and associated devices, signal conditioning and/or signal buffering circuitry. The memory **22** includes sufficient tangible, non-transitory memory such as magnetic or optical read-only memory, flash memory, etc., as well as random access memory, electrically erasable programmable read only memory, and the like. The controller **18** receives and records the measured joint positions (arrow **26**) from at least one position sensor **28**, and also monitors forces applied by or to the end-effector assembly **16** in the course of configuring the end-effector assembly **16**, as well as, while operating on a given workpiece (not shown). The controller **18** generates or receives input signals (arrow **30**) informing the controller **18** as to the required work task(s) to perform on the corresponding workpiece(s) and outputs control signals (arrow **32**) to the robot **12** to command the required actions from the robot **12**.

The robot **12** may be configured as a 6-axis industrial robot and may include a fixed or mobile base **34** and a plurality of robotic joints **36**, at least some of which are shown in FIG. **1**. The various joints **36** connect segments or serial linkages of the robot **12**, including a first or lower robotic arm **38**, a second or upper robotic arm **40**, and a wrist **42**, which collectively provide the desired range of motion and number of control degrees of freedom needed for performing assigned work tasks. It is contemplated that the robot **12** may include more or fewer robotic arms and wrists. Examples of such work tasks performed by the robot **12** include the grasping, lifting, locating, and placement of panels of metal or glass panes, along with a host of other possible tasks, such as painting and welding. Joint position sensors **28** may be positioned with respect to each joint **36** and configured to measure and report the measured joint positions (arrow **26**) to the controller **18**, as previously discussed. Additionally, one or more force sensors (not shown) may also be positioned with respect to the joints **36** and used to provide force or torque feedback to the controller **18**, which may avoid excessive force on the workpiece or the end-effector assembly **16**.

With respect to the end-effector assembly **16**, this structure may include a master boom **44** and a latticed end-effector array **46**. The end-effector array **46** in the depicted embodiments includes one frame rail **48** arranged orthogonally with respect to a longitudinal axis **50** of the master boom **44**. It is contemplated, however, that the end-effector array **46** may include more than one frame rail **48**. In the depicted embodiment, the frame rail **48** has a substantially cylindrical shape. The end-effector array **46** may also include a plurality of tool branches **52** movably coupled to the frame rail **48**. However, the end-effector array **46** may alternatively have only a single tool branch **52**. Each tool branch **52** includes a branch rail **54** and a tool module **56** cantilevered from the frame rail **48** and extending radially outward from the frame rail **48**. The various branch rails **54** are slidingly and rotatingly attached to the frame rail **48**. In other words, the branch rails **54** are movably coupled to the frame rail **48**, as will be described in greater detail below. Individual tool modules **56** are suspended from or movably coupled to the branch rails **54**. The frame rail **48** is connected, in turn, to the master boom **44** via a mechanical coupling **58**.

With reference now to FIG. **2**, the master boom **44** may include a double-sided tool changer assembly **60** having opposing tool changers **62**, **64**. The term "tool changer" refers to manual or automatic assemblies that enable rapid change out of robotic end-effectors. Such devices typically include integrated power and communications ports, connectors, and the like as needed for functioning of an end tool, such as grippers or vacuum suction cups **66**. In the depicted embodiment, the tool changer assembly **60** is specially configured to provide simultaneous engagement of the master boom **44** with both the robot **12** and the configuration stand **20**, the latter of which is shown schematically in FIG. **1**.

For the purposes of the present disclosure, the configuration stand **20** may be fixed with respect to a floor or suspended from a vertical surface such as a machine column or wall. The configuration stand **20** has a predetermined position in a Cartesian (e.g., XYZ) frame of reference, and thus provides a calibrated reference point for zeroing of the robot **12** during reconfiguration of the end-effector assembly **16**. For example, when transitioning from a first configuration to another configuration, the robot **12** connects the tool changer **64** to the configuration stand **20** and releases the tool changer **62**. As the robot **12** reconfigures the end-effector assembly **16**, the locations in free space of each of the locking mechanisms (e.g., branch locking mechanism **74** and swing locking mechanism **70**) described below is known to the controller **18** by virtue of the known location in the frame of reference provided by the configuration stand **20**. In the event the configuration of the end-effector assembly **16** becomes unknown during an operation (e.g., due to an impact event or power failure), the end-effector assembly **16**, while suspended from the configuration stand **20**, can be manually set to a calibrated setting in which the positions of the various end tools and locking mechanisms are known, with configuration thereafter commencing from the zeroed setting.

As described below with particular reference to FIGS. **2** and **3**, the branch rails **54** with attached tool modules **56** are automatically repositionable by the robot **12** using the configuration tool **14** and instructions executed by the controller **18**. Accordingly, the tool branches **52** may be arranged as desired to permit the tool modules **56**, or more precisely, the individual end tools **66** of the tool modules **56**, to attach to or otherwise interact with a given workpiece. In a non-limiting body panel example, the corresponding end tools **66** as shown in the various figures are configured as pneumatic suction cups or grippers of the type commonly used to secure and move automotive or other body panels without marring cosmetic show surfaces. However, other end tools **66**, such as pinchers, clamps, spray nozzles, may be used. Therefore, the particular construction of the end tools **66** may vary. In each tool branch **52**, a swing arm **68** is coupled between the end tool **66** and the branch rail **54** by a swing locking mechanism **70**, as will be described in greater detail below. The swing arm **68** is obliquely angled relative to the branch rail **54** in order to help the end tool **66** interact with a workpiece.

The end-effector assembly **16** can be reconfigured to interact with workpieces having different sizes, shapes, and/or surface contours relative to each other and other workpieces, and constructed from different materials. For example, a workpiece may be considerably larger and more uniform than another workpiece, thereby requiring different configurations of the same end-effector assembly **16**. Any number of possible workpieces may be encountered in a given manufacturing operation, and thus the end-effector assembly **16** is reconfigurable by the robot **12** to operate on any of them individually, as needed.

The controller **18** is made aware of the particular workpiece to be operated on via the input signals (arrow **30** of FIG. **1**), such as via manual selection by an operator, detection of an RFID tag, or any other suitable identifying process. The controller **18** then automatically selects a corresponding configuration from its memory **22**. After the end-effector assembly **16** has been deposited on the configuration stand **20** via the tool changer **64**, the robot **12** then releases the end-effector assembly **16** via the tool changer **62** and moves to attach the configuration tool **14** at a suitable workstation (not shown) to its wrist **42** or other suitable end linkage via another tool changer **142** mounted on the configuration tool **14** (see FIG. **6**) so as to configure the end-effector assembly **16**. Such a workstation may be embodied as a fixture that allows the configuration tool **14** to be retained at a calibrated position, i.e., a position readily accessible by the wrist **42**. All of this occurs while the end-effector assembly **16** remains captive on the configuration stand **20**. Furthermore, the present embodiment allows for the end-effector assembly **16** to be configured by the robot **12** without the need for any "flipping" on the configuration stand **20**, as the lock/unlock features of the swing lock **70** and the branch lock **74** are accessible from the opposite direction of the end tools **66**.

Once the end-effector assembly **16** has been fully configured for the task at hand using the configuration tool **14**, the robot **12** automatically deposits the configuration tool **14** to its workstation, detaches the configuration tool **14** from the wrist **42** via releasing the tool changer **142** on the configuration tool **14**, moves to pick up the newly configured end-effector assembly **16** by engaging the tool changer **62** and releasing the tool changer **64** at the same time, removes the end-effector assembly **16** from the configuration stand **20**, and commences operation on a workpiece. The ability of the robot **12** to reconfigure the end-effector assembly **16**, without flipping the end-effector assembly **16**, allows for its use across a wide range of possible workpieces and in a variety of different environments, without concern for space limitation. In this way, manufacturing flexibility and efficiency can be enhanced, while reducing tooling costs and system downtime.

Referring to FIG. **2**, the end-effector assembly **16** includes at least one frame rail **48** arranged orthogonally with respect to the boom axis **50** of the main boom **44**, with the various tool modules **56** connected with respect to the radially-extending branch rails **54**. In an example embodiment in which the end tools **66** are pneumatic grippers, pneumatic tubing may be routed along the main boom **44** and directed to the various end tools **66**.

With reference to FIGS. **2** and **3**, each tool branch **52** includes a branch lock **74** coupling the branch rail **54** to the frame rail **48**. In the depicted embodiment, the branch lock **74** can move between a locked and an unlocked state. In the locked state, the branch lock **74** fixes the position of the branch rail **54** relative to the frame rail **48** and, therefore, the branch rail **54** remains stationary relative to the frame rail **48**. When the branch lock **74** is in the unlocked state, the branch rail **54** can translate along the frame rail **48** in the directions indicated by arrow **76** and can rotate about the frame rail **48** in the directions indicated by arrow **78**. In this manner, any number of different configurations of the tool modules **56** may be set by the robot **12** as needed in response to the commands (arrow **32**) from the controller **18**. Due to its rounded cross-section (e.g., circular cross-section), the frame rail **48** allows the branch lock **74** to rotate about the frame rail axis **80** when the branch lock **74** is in the unlocked state. In addition, the branch lock **74** can slide along the frame rail axis **80** when it is disposed in the unlocked state. As discussed in detail below, the configuration tool **14** can be used to move the branch lock **74** between the locked and unlocked states.

In the depicted embodiment shown in FIGS. **3** and **4**, the branch lock **74** includes a clamp **82** for clamping the frame rail **48**. The clamp **82** is configured as a wrap-around clamp and includes a clamp base **84** and a clamp arm **86** movably coupled to the clamp base **84**. The clamp base **84** and clamp arm **86** define a clamp recess **88** configured, shaped, and sized to receive a portion of the frame rail **48**. The clamp recess **88** may have a concave shape in order to allow the frame rail **48** to seat on the clamp base **84**.

A fastener **96** can be used to adjust the distance between the clamp base **84** and the clamp arm **86**. As non-limiting examples, the fastener **96** may be a screw, a bolt, or any other suitable fastener for moving the clamp arm **86** toward or away from the clamp base **84**. In the depicted embodiment, for example, the fastener **96** is a bolt having a head portion arranged outside the clamp arm **86** and a nut arranged outside the clamp base **84**. As should be understood, rotating the fastener **96** causes the nut to move the clamp arm **86** towards or away from the clamp base **84**, thereby tightening or loosening the clamp **82** with respect to the frame rail **48**. Specifically, rotating the fastener **96** in a first rotational direction (e.g., clockwise) locks the clamp **82**, and rotating the fastener **96** in an opposite direction (e.g., counterclockwise) unlocks the clamp **82**. When the clamp **82** is locked, the branch rail **54** is fixed with respect to the frame rail **48**, and therefore, remains stationary relative to the frame rail **48**. When the clamp **82** is unlocked, the branch rail **54** can translate and rotate relative to the frame rail **48**. The clamp **82** may also be configured as a two-part clamp with one hinge, a double-hinged three-part clamp, or any other suitable clamp design.

The branch lock **74** may further define a plurality of lugs or tabs **97** providing a feature for the configuration tool **14** to engage and adjust the branch lock **74**, as will be described in greater detail below. At least one of the tabs **97** may incorporate a centering feature for use in alignment control by the robot **12**. The branch lock **74** additionally includes a permanent clamp **98** that holds the branch rail **54** orthogonal relative to the frame rail **48**.

With continued reference to FIGS. **2** and **3**, each tool branch **52** may also include a swing locking mechanism **70** coupling the branch rail **54** to the swing arm **68**. In the depicted embodiment, the swing lock **70** can move between the locked and unlocked states. In the locked state, the swing lock **70** fixes the position of the swing arm **68** relative to the branch rail **54** and, therefore, the swing arm **68** remains stationary relative to the branch rail **54**. When the swing lock **70** is in the unlocked state, the swing arm **68** can translate along the branch rail **54** in the directions indicated by arrow **100**, can rotate about the branch rail **54** in the directions indicated by arrow **102**, and can rotate about a pivot shaft **104** (see FIG. **5**) in the directions indicated by arrow **103**. In this manner, any number of different configurations of the tool modules **56** may be set by the robot **12** as needed in response to the commands (arrow **32**) from the controller **18**. Due to its rounded cross-section (e.g., circular cross-section), the branch rail **54** allows the swing lock **70** to rotate about the branch rail axis **105** when the swing lock **70** is in the unlocked state. In addition, the swing lock **70** can slide along the branch rail axis **105** when it is disposed in the unlocked state. As discussed in detail below, the configuration tool **14** can be used to move the swing lock **70** between the locked and unlocked states.

Referring now to FIG. **5**, the swing lock **70** includes a wrap-around clamp **106** for clamping the swing arm **68** to the branch rail **54**, the pivot shaft **104** for rotationally securing the swing arm **68** to the wrap-around clamp **106**, a swing plate **108** for engagement with the configuration tool **14**, a joining mechanism **110** for securing the pivot shaft **104** to the swing arm **68**, and a locking fastener **112** for tightening and releasing the swing lock **70**. In particular, the wrap-around clamp **106** can be clamped and/or loosened on the branch rail **54** by pinching and/or releasing a pair of split flanges (i.e., split flange base **114**, split flange arm **116**). The wrap-around clamp **106** further includes a frusto-conical wedge **118** protruding from the split flange base **114** toward the swing arm **68**. The swing arm **68** defines a corresponding frusto-conical recess **120** configured, shaped, and sized to receive the frusto-conical wedge **118** in order to enhance the clamping force between the wrap-around clamp **106** and the swing arm **68**.

The swing arm **68** may be tightened to the wrap-around clamp **106** when in the locked state, but is free to rotate with the pivot shaft **104** fastened via the joining mechanism **110** (e.g., a bolt, screw, dowel pin, weld) when in the unlocked state. To this end, the pivot shaft **104** may extend through openings in the split flange base **114** and split flange arm **116** and terminate at the swing plate **108**. The pivot shaft **104** may be keyed to the swing plate **108** via at least one key **122**, which secures the pivot shaft **104** to the swing plate **108** rotationally, but not axially.

The locking fastener **112** can movably couple the split flange base **114** to the split flange arm **116**. As non-limiting examples, the locking fastener **112** may be a screw, a bolt, or any other suitable fastener including external threads. In the depicted embodiment, for example, the locking fastener **112** is a captured fastener secured within the swing plate **108** via a retaining ring **124**. In this way, when unclamping, the locking fastener **112** freely spins, but the pivot shaft **104** may be pushed away axially to separate and cause the locking fastener **112** to push back the configuration tool **14** instead of the frusto-conical wedge and recess **118**, **120**, which may otherwise remain frictionally wedged together.

The locking fastener **112** further includes a shaft **126** and a head **128** coupled to the shaft **126**. The head **128** is arranged to protrude from the swing plate **108**, while the shaft **126** is partially disposed in a blind hole **130** extending through the pivot shaft **104**. The blind hole **130** of the pivot shaft **104** is internally threaded and is configured, shaped, and sized to mate with an external thread of the shaft **126**. As a result, rotating the locking fastener **112** causes the split flange base **114** and the split flange arm **116** to move together or apart, thereby tightening or loosening the wrap-around clamp **106** with respect to the branch rail **54** and the swing arm **68**, concurrently. Specifically, rotating the locking fastener **112** in a first rotational direction (e.g., clockwise) threads the locking fastener **112** into the pivot shaft **104** and locks the wrap-around clamp **106**, while rotating the locking fastener **112** in an opposite direction (e.g., counterclockwise) unthreads the locking fastener **112** from the pivot shaft **104** and unlocks the wrap-around clamp **106**.

During unclamping, frictional forces between the frusto-conical wedge and recess **118**, **120** may bind the swing arm **68** to the frusto-conical wedge **118** while the split flange base **114** and the split flange arm **116** continue to move apart. The over-stretch limiter **131**, however, prevents this from happening, for example, via a threaded end fastened to a mating threaded hole in the split flange arm **116** and a head loosely held in the axial direction inside a counter bore in the split flange base **114**. The axial movement between the split flange base and arm **114**, **116** will cause the head of the over-stretch limiter **131** to contact the bottom of the counter bore and stop the separation between the split flange base and arm **114**, **116**, which in turn redirects the unclamping energy towards separating the frusto-conical wedge and recess **118**, **120**. In this way, the swing arm **68** can rotate about the axis of the pivot shaft **104**, while also translating and rotating about the axis of the branch rail **54** when the swing lock **70** is in the unlocked state.

In addition, a pneumatic fitting **132** may be coupled to the pivot shaft **104** in order to fluidly couple pneumatic tubing to the end tools **66** arranged on the swing arm **68**. The pneumatic fitting **132** may be in fluid communication with a fluid passage **134** formed through the pivot shaft **104**. The swing plate **108** may further define a plurality of lugs or tabs **136** providing a feature for the configuration tool **14** to engage and adjust the wrap-around clamp **106**, as will be described in greater detail below. At least one of the tabs **136** may incorporate a centering feature for use in alignment control by the robot **12**.

With specific reference to FIG. **6** and FIG. **7**, the configuration tool **14** includes an axially-extending tool assembly **140** and a tool changer **142** coupled to the tool assembly **140** via axially-extending support rails **144**. The tool assembly **140** includes a tool body **146**, which may include parallel plates **148** each shaped as a rectangle or another polygon. Each parallel plate **148** is mounted to (and extends from) a first end plate **150** toward a second end plate **152**. The first and second end plates **150**, **152** are part of the tool body **146** and may be rectangular in shape. The first end plate **150** may be larger in area than the second end plate **152** to facilitate use in configuring the end-effector assembly **16**.

A nutrunner **154** can rotate about a nutrunner axis **156** (i.e., bit axis) and extends through the second end plate **152** and is used to adjust the branch lock **74** and the swing lock **70**. In the present disclosure, the term "nutrunner" means a powered torque wrench capable of using pneumatic, electric, or hydraulic power to rotate and transmit torque. The nutrunner **154** may be driven with a servo motor and control for precise and consistent rotation.

In addition, the tool assembly **140** includes a gripper **158** coupled to the tool body **146** at a location closer to the second end plate **152** than to the first end plate **150**. The gripper **158** is parallel to the nutrunner **154** and includes a gripper actuator **160** and a plurality of gripper fingers **162** movably coupled to the gripper actuator **160**. The gripper actuator **160** can be an electric or pneumatic actuator, and the tool changer **142** can channel electricity or pneumatic fluid for controlling the gripper **158** when the configuration tool **14** is mounted to the wrist **42**. In the depicted embodiment, the gripper **158** includes two fingers **162**. However, the gripper **158** may include more than two fingers **162**. Irrespective of the quantity, the gripper fingers **162** can move relative to one another between a first or disengaged position (FIG. **6**) and a second or engaged position (FIG. **7**). When disposed in the first position (FIG. **6**), the gripper fingers **162** are closer to each other than in the second position (FIG. **7**). The gripper fingers **162** may be coupled to the gripper actuator **160** via a sliding member **164**. The sliding member **164** is coupled to the gripper fingers **162** and can be actuated by the gripper actuator **160** in order to move the gripper fingers **162** between the first and second positions.

The gripper fingers **162** of the gripper **158** are configured to grasp the tabs **97** of the branch lock **74** in order to hold the branch lock **74**, thereby allowing the configuration tool **14** to move (translate or rotate) the tool branch **52** relative to the frame rail **48**. Similarly, the gripper fingers **162** of the gripper **158** can grasp the tabs **136** of the swing lock **68** in order to hold the swing plate **108**, thereby allowing the configuration tool **14** to move (e.g., rotate or translate) the tool module **56** relative to the branch rail **54**. In particular, to release the swing lock **68**, the configuration tool **14** is robotically commanded to grasp the swing plate **108** on the tabs **136**, then the nutrunner **154** turns the locking fastener **112** counter-clockwise to push the pivot shaft **104**, and thus the swing arm **68**, away from the frusto-conical wedge **118**. In turn, this allows the robot **12** to slide and rotate the tool branches **52** around the frame rail **48**, as well as to slide and rotate the swing arm **68** in combination for moving the end tools **66** to the desired position. Similarly, to lock the swing lock **68** upon reaching a desired position, and while the configuration tool **14** is still engaged, the nutrunner **154** turns the locking fastener **112** clockwise to pull in the pivot shaft **104** and the swing arm **68** together to thereby engage the frusto-conical wedge **118** and the frusto-conical recess **120**. In turn, this pinches the split flanges **114**, **116** of the wrap-around clamp **106** over the branch rail **54**, thereby securely locking the end-effector assembly **16** into position.

The tool changer **142** of the configuration tool **14** may be any suitable mechanical coupling, similarly to the tool changer **62** on the master boom **44**, allowing the robot **12** to pick up the configuration tool **14** and includes guide pins **166** or other suitable coupling devices which enable the robot **12** to engage the configuration tool **14** with the wrist **42**. The tool changer **142** may also include electrical and pneumatic ports capable of channeling electric and pneumatic power and control signals to run the nutrunner **154** via a drive motor inside the nutrunner **154**. Once coupled to the wrist **42**, the configuration tool **14** locks into place and electrical and/or pneumatic power is provided to the nutrunner **154** as needed to rotate the driver bit **168**, e.g., a hex-head bit. Thus, actuating the nutrunner **154** causes the driver bit **168** to turn. At least part of the nutrunner **154** extends through the second end plate **152** in a direction away from the first end plate

150, such that the driver bit 168 is outside the tool body 146 and extends beyond the second end plate 152.

Referring to FIG. 8 and FIG. 9, in order to reconfigure the tool branch 52, the configuration tool 14 is manipulated first to engage the nutrunner 154 and its driver bit 168 with the fastener 96 of the branch lock 74 that wraps around on the frame rail 48, while the gripper fingers 162 on the configuration tool 14 remain in the first position (i.e., in the disengaged position) but in a position that is ready to engage with at least one of the tabs 97. Specifically, the robot 12 moves the configuration tool 14 toward the branch lock 74 such that the driver bit 168 is aligned with the fastener 96 and the gripper fingers 162 of the gripper 158 are aligned with at least one of the tabs 97, while the gripper fingers 162 are in the first position (i.e., disengaged state). The configuration tool 14 may be moved toward the branch lock 74 until the driver bit 168 is aligned with the fastener 96 and the gripper fingers 162 are aligned with at least one of the tabs 97. Then, as best shown in FIG. 9, the gripper fingers 162 are then moved to the second position (i.e., engaged state) in order to grasp at least one of the tabs 97. As discussed above, the gripper fingers 162 can be actuated pneumatically or electrically.

Next, the controller 18 electrically commands the nutrunner 154 to engage the driver bit 168 with the fastener 96. The driver bit 168 may rotate (e.g., counter-clockwise) to loosen the fastener 96 and release the branch lock 74 from secure engagement on the frame rail 48. With the gripper fingers 162 of the configuration tool 14 grasping tightly against the at least one of the tabs 97, the robot 12 can slide the branch rail 54 along the frame rail 48, as well as, rotate the branch rail 54 around the frame rail 48 to the desired position or orientation. Afterwards, the nutrunner 154 of the configuration tool 14 is commanded (by the controller 18) to rotate (e.g., clockwise) to tighten the fastener 96 to secure the branch lock 74 in the desired position on the frame rail 48. The controller 18 can also command the gripper fingers 162 to disengage (i.e., move to the first position) in order to release the at least one of the tabs 97 and disengage the configuration tool 14 from the branch lock 74 to complete the reconfiguration operation.

With reference now to FIG. 10 and FIG. 11, in order to configure the swing arm 68 or adjust the position and/or orientation of the end tool 66 (e.g., vacuum gripper), the configuration tool 14 may be manipulated to engage the nutrunner 154 and its driver bit 168 with the locking fastener 112 of the swing lock 70, while the gripper fingers 162 on the configuration tool 14 remain disengaged (i.e., in the first position) but in a position that is ready to engage with the locking fastener 112. Specifically, the robot 12 moves the configuration tool 14 toward the swing lock 70 such that the driver bit 168 is aligned with the locking fastener 112 and the gripper fingers 162 of the gripper 158 are aligned with at least one of the tabs 136, while the gripper fingers 162 are in the first position (i.e., disengaged state). The configuration tool 14 may be moved toward the swing lock 70 until the driver bit 168 is aligned with the head of the locking fastener 112 and the gripper fingers 162 are aligned with at least one of the tabs 136. Then, as best shown in FIG. 11, the gripper fingers 162 are engaged (i.e., moved to the second position) in order to grasp at least one of the tabs 136. As discussed above, the gripper fingers 162 can be actuated pneumatically or electrically.

Next, the controller 18 electrically commands the nutrunner 154 to engage the driver bit 168 with the locking fastener 112. The driver bit 168 may rotate (e.g., counter-clockwise) to loosen or push the locking fastener 112 away from the pivot shaft 104. This action, in turn, allows the frusto-conical wedge 118 to move away from the frusto-conical recess 120, thereby releasing the swing lock 70 from secure engagement on the branch rail 54, while concurrently allowing the swing arm 68 to move with respect to the swing lock 70. With the gripper fingers 162 of the configuration tool 14 grasping tightly on the at least one of the tabs 136, the robot 12 can slide the swing arm 68 along the branch rail 54, as well as, rotate the tool module 56 around the branch rail 54 to the desired position or orientation. Additionally, the robot 12 can also rotate the swing arm 68 and the end tool 66 (e.g., vacuum gripper) around the axis of the pivot shaft 104. Afterwards, the nutrunner 154 of the configuration tool 14 is commanded (via the controller 18) to rotate (e.g., clockwise) to tighten the locking fastener 112 to secure the swing lock 70 in the desired position on the branch rail 54, as well as, to secure the frusto-conical wedge 118 in the frusto-conical recess 120 in order to secure the swing arm 68 in the proper orientation with respect to the swing lock 70. Then, the controller 18 can also command the gripper fingers 162 to disengage (i.e., move to the first position) to release the tabs 136 and disengage the configuration tool 14 from the swing lock 70 to complete the reconfiguration operation.

With reference now to FIG. 12, another exemplary swing lock 270 for the reconfigurable end-effector assembly 16 incorporates a wrap-around clamp 306 for clamping a swing arm 268 to the branch rail 54, a pivot shaft 308 for rotationally securing the swing arm 268 to the wrap-around clamp 306, a swing plate 310 for engagement with the configuration tool 14, and a locking fastener 312 for tightening or releasing the swing lock 270. With reference to the drawings, wherein like reference numbers refer to like components, the wrap-around clamp 306 can be clamped and/or loosened on the branch rail 54 by pinching and/or releasing a pair of split flanges of the wrap-around clamp 306 (i.e., split flange base 314, split flange arm 316), as previously described with respect to the swing lock 70. However, rather than utilizing the frusto-conical wedge and recess 118, 120 to enhance the clamping force between the wrap-around clamp 306 and the swing arm 268, the assembly is fixed between the wrap-around clamp 306 and a flange 370 of the pivot shaft 308. The swing arm 268 can be rotationally secured to the pivot shaft 308 through the use of a key 372 and clamp assembly 374 at a distal end 376 of the swing arm 268. In an alternate arrangement, the swing arm 268 may also be arranged within so as to be fixed between the wrap-around clamp 306 and the flange 370 of the pivot shaft 308.

As previously discussed, the swing arm 268 may carry the end tool 266. Furthermore, the swing arm 268 may have a similar locked and unlocked state as the swing arm 68 dictated by the tightening or releasing the locking fastener 312 with respect to the swing plate 310.

Embodiments of the present disclosure are described herein. This description is merely exemplary in nature and, thus, variations that do not depart from the gist of the disclosure are intended to be within the scope of the disclosure. The figures are not necessarily to scale; some features could be exaggerated or minimized to show details of particular components. Therefore, specific structural and functional details disclosed herein are not to be interpreted as limiting, but merely as a representative basis for teaching one skilled in the art to variously employ the present invention. As those of ordinary skill in the art will understand, various features illustrated and described with reference to any one of the figures can be combined with features illustrated in one or more other figures to produce embodiments that are not explicitly illustrated or described. The combinations of features illustrated provide representative embodiments for various applications. Various combinations and modifications of the features consistent with the teachings of this disclosure, however, could be desired for particular applications or implementations.

What is claimed is:

1. An end-effector assembly comprising:

a master boom;

a frame rail coupled to the master boom;

at least one branch rail movably coupled to the frame rail by a branch lock; and

a swing arm movably coupled to the at least one branch rail by a swing lock, wherein the swing lock further includes:

a clamp configured to movably secure the swing arm to the branch rail, wherein the clamp further defines a protrusion on an end face and the swing arm defines a correspondingly-shaped recess, and wherein the protrusion and the recess are matingly joined when the locking fastener is locked;

a pivot shaft extending through the clamp and the swing arm, the pivot shaft configured to rotationally secure the swing arm to the clamp;

a swing plate secured to the pivot shaft and configured for engagement with a configuration tool; and

a locking fastener extending through the swing plate and into the pivot shaft, wherein the locking fastener is configured to lock and unlock the swing lock in position along the branch rail.

2. The end-effector assembly of claim **1**, wherein the branch lock is movable relative to the frame rail between an unlocked and a locked state so as to fix the branch rail in position relative to the frame rail.

3. The end-effector assembly of claim **1**, wherein the swing lock is rotationally and linearly movable along the branch rail between an unlocked and a locked state so as to fix the swing arm in position relative to the branch rail.

4. The end-effector assembly of claim **1**, further comprising an end tool arranged at a distal end of the swing arm, the end tool defining a first side of the end-effector assembly for engagement with a workpiece, wherein the branch lock and the swing lock are configured to be engaged by the configuration tool on a second side of the end-effector assembly opposite to the first side.

5. The end-effector assembly of claim **1**, further comprising a retaining ring secured within the swing plate and configured to retain the locking fastener therein, wherein the retaining ring traps the locking fastener to assist in releasing the protrusion from the recess.

6. The end-effector assembly of claim **1**, wherein the swing lock further comprises at least one over-stretch limiting device.

7. The end-effector assembly of claim **6**, wherein the over-stretch limiting device includes at least one over-stretch fastener secured within the clamp for restraining the clamp during unlock of the swing lock.

8. A swing lock assembly for an end-effector, the swing lock assembly comprising:

a clamp configured to movably secure a swing arm to a branch rail, the clamp including an arm portion and a base portion having a protrusion on an end face thereof, the swing arm having a recess correspondingly shaped with the protrusion;

a pivot shaft extending through the arm and base portions of the clamp, the pivot shaft configured to rotationally secure the swing arm to the clamp;

a swing plate arranged on the arm portion of the clamp and keyed to the pivot shaft, the swing plate including at least one tab configured for engagement with a configuration tool;

a locking fastener extending through the swing plate and into the pivot shaft, the locking fastener configured to lock and unlock the swing lock assembly in position along the branch rail, wherein the protrusion and the recess are matingly joined when the locking fastener is locked; and

a retaining ring secured within the swing plate and configured to retain the locking fastener therein, wherein the retaining ring traps the locking fastener to assist in releasing the protrusion from the recess.

9. The swing lock assembly of claim **8**, wherein the swing lock is rotationally and linearly movable along the branch rail between an unlocked and a locked state so as to fix the swing arm in position relative to the branch rail.

10. The swing lock assembly of claim **8**, further comprising an end tool arranged at a distal end of the swing arm, the end tool defining a first side of the end-effector, wherein the swing lock assembly is configured to be engaged by the configuration tool on a second side of the end-effector opposing the first side.

11. The swing lock assembly of claim **8**, further comprising at least one over-stretch limiting device having at least one over-stretch fastener secured between the arm portion and the base portion of the clamp for restraining the clamp during unlock of the locking fastener.

12. The swing lock assembly of claim **8**, wherein the configuration tool includes:

a tool body;

a gripper coupled to the tool body, the gripper including a plurality of gripper fingers movable toward and away from each other, wherein the configuration tool is coupled to the swing lock assembly when the gripper fingers engage the at least one tab; and

a driver bit extending from the tool body, wherein the driver bit is aligned with the locking fastener when the gripper fingers engage the at least one tab such that rotating the driver bit causes the swing lock assembly to move between the locked and unlocked states.

13. A swing lock assembly for an end-effector, the swing lock assembly comprising:

a clamp configured to secure a swing arm to a branch rail, the clamp having a first surface and an opposing second surface;

a pivot shaft extending through the clamp and the swing arm in order to rotationally secure the swing arm to the clamp, the pivot shaft having a flange arranged at the second surface of the clamp, and wherein the pivot shaft is keyed for rotational movement with the swing arm;

a swing plate arranged on the first surface of the clamp and keyed to the pivot shaft, the swing plate including at least one tab configured for engagement with a configuration tool; and

a locking fastener extending through the swing plate and into the pivot shaft, the locking fastener configured to move the swing plate and the flange toward each other in order to lock the swing lock assembly in position along the branch rail, and away from each other in order to unlock the swing lock assembly from position along the branch rail.

14. The swing lock assembly of claim **13**, wherein the swing lock assembly is rotationally and linearly movable along the branch rail between an unlocked and a locked state so as to fix the swing arm in position relative to the branch rail.

15. The swing lock assembly of claim **13**, further comprising an end tool arranged at a distal end of the swing arm, the end tool defining a first side of the end-effector, wherein the swing lock assembly is configured to be engaged by the configuration tool on a second side of the end-effector opposing the first side.

16. The swing lock assembly of claim **13**, wherein the configuration tool includes:

a tool body;

a gripper coupled to the tool body, the gripper including a plurality of gripper fingers movable toward and away from each other, wherein the configuration tool is coupled to the swing lock assembly when the gripper fingers engage the at least one tab; and

a driver bit extending from the tool body, wherein the driver bit is aligned with the locking fastener when the gripper fingers engage the at least one tab such that rotating the driver bit causes the swing lock assembly to move between the locked and unlocked states.

17. A robot having an end-effector including the swing lock assembly of claim **13**.

* * * * *